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14. ABSTRACT
A method is disclosed for calibration of a towed line array. In a low frequency band, calibration is performed using an acoustic field observed by reference standard hydrophones. The observations form a model of a complex acoustic field throughout a space occupied by a measurement apparatus. The array sensitivities are computed by comparing output voltages of the array with the acoustic field estimated at the locations occupied by hydrophones of the array. Variations in the acoustic field that cannot be accounted for by free field propagation theory are included in the calculation of array channel sensitivities. The method extends the low frequency limit for the calibration to less than the minimum frequency at which free field propagation conditions can be approximated. Boundary reflections and spatial variations in the acoustic field are recognized. The spatial distribution of acoustic energy is used to provide low frequency calibration with improved precision.

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SYSTEM AND METHOD FOR THE CALIBRATION OF A HYDROPHONE LINE ARRAY

[0001] This application claims the benefit of United States Provisional Patent Application Number 61/885,769; filed on October 2, 2013 by the inventors, Steven E. Crocker, Daniel C. Casimiro, Robert F. Cutler, Ronald R. Smalley and entitled "METHOD FOR THE CALIBRATION OF A HYDROPHONE LINE ARRAY"

STATEMENT OF GOVERNMENT INTEREST

[0002] The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefore.

BACKGROUND OF THE INVENTION

(1) Field of the Invention

[0003] The present invention is a comparison calibration of hydrophone data channels in a towed line array of hydrophones in which the comparison calibration extends a low frequency limit that is applicable to existing calibration methods that seek to approximate free field propagation in open water.

(2) Description of the Prior Art

[0004] Among the principle challenges in the calibration of a hydrophone towed line array is the large size of the array itself. Hydrophone line arrays can have lengths of hundreds (or thousands) of meters. Thus, acoustic calibration of hydrophone line arrays under controlled laboratory conditions is not generally practiced (nor feasible).

[0005] Calibration of a towed hydrophone line array is typically performed using a comparison method. When calibrating, one of more reference standard hydrophones with a known free field voltage sensitivity (FFVS) are used to measure an acoustic field that is transmitted by an acoustic projector at one or more locations in the vicinity of a test article (the towed hydrophone line array). The FFVS is a complex quantity with a magnitude and a phase. The magnitude is traditionally expressed as decibels relative to one volt per micro Pascal (e.g., dB re 1V/uPa) and the phase is expressed in degrees.

[0006] A problem when using acoustic free field or gated continuous wave calibration techniques for towed line arrays is the low frequency limit that is imposed by a requirement for reflection free signals. Various methods have been developed to calculate the FFVS of large numbers of hydrophones distributed over the length of the towed line arrays [See L.J. Hix "Method and Apparatus for Testing Marine Seismic Cables" United States Patent No. 4,160,228].

[0007] The Hix reference discloses a method by which the array to be calibrated is towed past a stationary acoustic projector in an open body of water. The acoustic projector transmits acoustic signals with known properties. The electrical outputs of the array hydrophones are recorded on the tow ship where individual channel outputs are compared with one another. Since the channel outputs are not compared to a calibrated reference standard; the FFVS of the array channels are not provided. This practice is often referred to as a relative calibration.

[0008] In Skinner ("Place Calibration of Sonar Receive Array"; United States Patent No. 6,208,584), a method is disclosed whereby both a test article and an acoustic projector are towed behind a ship in an open body of water. The method compares the magnitude and phase of the hydrophone channel outputs in the test article. However, an independent reference standard hydrophone is not used; therefore, the FFVS is not provided by this relative calibration method.

[0009] Percy ("Hydrophone Line Array Calibration Unit", United States Patent No. 3,959,620) teaches a method by which a hydrophone line array is affixed to a cylindrically shaped wire mesh framework. One calibrated reference standard hydrophone is also affixed to the framework to provide an absolute reference for comparison. This practice is often referred to as an absolute calibration.

[0010] The Percy reference includes an acoustic projector located at an approximate geometric center of the cylindrical test fixture. The acoustic projector is used to transmit acoustic interrogation signals to a test article and reference hydrophone. The cited reference does not teach a method of support for the acoustic projector to prevent the transmission of vibration into the cylindrical test fixture, array and reference standard hydrophone. Such vibrations tend to corrupt the received acoustic data; thus, introducing both random and systematic errors into the calibration result.

[0011] The Percy reference also assumes the existence of an acoustically non-reflective test tank in which the calibration is performed over a frequency range of 10 to 1000Hz. The cited reference does not teach a method to create acoustically non-reflective test tank surfaces, nor is a method taught to render the water surface to be acoustically non-reflective. Acoustic test tanks with the non-reflective properties assumed by the Percy reference are not known in the prior art. Thus, acoustic data will likely contain contributions from reflected acoustic energy with commensurate errors in the FFVS computed for the array hydrophone channels.

[0012] Most acoustic calibration procedures, including those taught by the Hix, Skinner, and Percy references; tacitly assume that the properties of the acoustic field are known to arbitrary precision. Indeed, this is typically the case for calibration tests conducted in the highly controlled environment of an enclosed laboratory. However, this is rarely the case for calibrations performed in open water where boundary reflections may be unavoidable.

[0013] When performing acoustic measurement in an open body of water (such as lakes, ponds and pools used by acoustic test facilities); there exists a minimum frequency at which free field propagation can be simulated by appropriate gating of the time series signals such that reflections from the boundaries (surface, bottom and sides) can be excluded. Above this limiting frequency, a time gated acoustic waveform can be transmitted and received on the reference standard hydrophones and the array hydrophones (test article) under approximately free field conditions.

[0014] Reflections from the surface or other boundaries are eliminated by appropriate time gating of the received signals. In this frequency band, calibration of the test article can be performed using techniques taught by the prior art [See "American National Standard: Procedures for Calibration of Underwater Electroacoustic Transducers", ANSI/ASA S1.20-2012].

[0015] As discussed previously, this method has a low frequency limit governed by the requirement to approximate free field conditions. At lower frequencies, it is not possible to collect time series data of sufficient length without including acoustic field components that are reflected from the water surface or other boundaries.

SUMMARY OF THE INVENTION

[0016] The present invention discloses a method for comparison calibration of hydrophone data channels in a towed line array comprising individual hydrophones (or interconnected groups thereof). The free field voltage sensitivity (FFVS) of a hydrophone channel is defined for the purposes of this invention as the ratio of the complex voltage (e.g. magnitude and phase)output by the hydrophone and the complex acoustic pressure in the vicinity of the hydrophone. "Complex" quantities as used in the present invention indicate that a quantity has both a magnitude and a phase (or real and imaginary part) in the mathematical sense.

[0017] The method provides transmission of a continuous Gaussian noise waveform such that the statistics of the acoustic field in the volume of water occupied by a measurement apparatus or testing device are stationary. In this frequency band, the calibration is performed using a novel representation of the acoustic field observed by a plurality of calibrated reference standard hydrophones.

[0018] These acoustic field observations are used to form an empirical model of the complex acoustic field (e.g. magnitude and phase) throughout the spatial domain occupied by the measurement apparatus or testing device. "Empirical" as used in the present invention is based on or concerned with, or verifiable by observation or experience rather than theory or pure logic. The empirical model is based on the observed data, and does not assume a particular solution to the acoustic wave equation when describing the geometry of the acoustic field.

[0019] The test article sensitivities are then computed by a comparison of output voltages of the test article with the acoustic field estimated at the locations occupied by hydrophones of the test article. Spatial variations in the acoustic field that cannot be accounted for by free field propagation theory (e.g. boundary reflections) are observed and included in the calculation of array channel sensitivities.

[0020] The method extends the low frequency limit for the calibration to substantially less than the minimum frequency at which free field propagation conditions can be approximated.

The low frequency limit is determined by the minimum operating frequencies of the acoustic projector, the reference standard hydrophone, and/or the test article. The high frequency limit is determined by the spatial sampling density of the reference standard hydrophones. The nominal effective bandwidth when using eight reference standard hydrophones to monitor signals transmitted by a low frequency acoustic projector in the range of 20 to 300 Hz.

[0021] A principle difference between the prior art and the present invention is the employment of a non-idealized representation of the acoustic field used to interrogate the test article. The method of the present invention extends the low frequency calibration limit to well below the frequency at which it is possible to approximate free field propagation in open water.

[0022] The prior art presumes the existence of an acoustic field propagating into free space without any contribution or disturbance from boundary reflections. The present invention explicitly recognizes the existence of boundary reflections and the resultant spatial variations in the acoustic field. The spatial distribution of acoustic energy is observed and used to provide low frequency calibration with improved precision and accuracy despite the presence of reflected acoustic energy.

BRIEF DESCRIPTION OF THE DRAWINGS

[0023] A more complete understanding of the invention and many of the attendant advantages thereto will be readily appreciated as the same becomes better understood by reference to the following detailed description when considered in conjunction with the accompanying drawings wherein like reference numerals and symbols designate identical or corresponding parts throughout the several views and wherein:

[0024] **FIG. 1** depicts a hydrophone line array (a test article) helically affixed to a measurement apparatus of the present invention;

[0025] **FIG. 2** depicts a representative set of acoustic field components that are present when testing;

[0026] **FIG. 3** illustrates a magnitude of complex acoustic transfer function over a surface of a measurement apparatus relative to a principle reference hydrophone located at an azimuth angle of zero degrees and a vertical displacement of zero meters;

[0027] **FIG. 4** illustrates a phase of complex acoustic transfer function over a surface of a measurement apparatus relative to a principle reference hydrophone located at an azimuth angle of zero degrees and a vertical displacement of zero meters and which shows that the corresponding variation on phase was more than fifteen degrees;

[0028] **FIG. 5** illustrates the result of one round robin calibration with frequency compared to magnitude; and

[0029] **FIG. 6** illustrates the result of one round robin calibration with frequency compared to phase.

DETAILED DESCRIPTION OF THE INVENTION

[0030] Referring to the figures, **FIG. 1** depicts a hydrophone line array **100** (a test article) helically affixed to a measurement apparatus **10** (test fixture) composed of hollow circular tubes **12** joined by vertical supports **14** and covered with a wire mesh **16** that is substantially open to the passage of acoustic waves Both the circular tubes **12** and the vertical supports **14** are perforated by a plurality of holes that allow water to enter and air to escape when the measurement apparatus **10** and the test article **100** are submerged. In this way, reflection and scattering of acoustic energy from the test article **100** is reduced.

[0031] A plurality of brackets **18** are arranged at the bottom of the measurement apparatus **10** to support the test article **100** as the test article is installed onto the outer surface of the apparatus. The test article **100** is affixed to the measurement apparatus **10** using tie-wraps (not shown)or similar securing devices. The measurement apparatus **10** can be raised and lowered using a cable and sling **30** with the aid of an overhead crane (not shown).

[0032] An acoustic projector **32** is used to transmit the acoustic signals into the water in the vicinity of the measurement apparatus **10**. The acoustic projector **32** is suspended from a lifting device **34** that is attached to the sling **30** and supports the measurement apparatus **10**. The lifting device **34** includes a vibration isolator **36** for reducing the amplitude of vibrations that are transmitted from the acoustic projector **32** thru the sling **30** to the measurement apparatus **10** and ultimately to the hydrophone line array (test article **100**) being calibrated.

[0033] The vibration isolator **36** includes an elastic strap with tensile strength sufficient to attenuate the transmission of vibration along its length. Suitable vibration isolators are known in the art. In this instance and by using a standard vibration isolator, the static deflection when supporting the acoustic projector **32** in air is minor as compared to the size of the measurement apparatus **10** (approximately eight centimeters in this instance). The cutoff frequency for the example vibration isolator **36** would be less than three Hz. Thus, vibration at frequencies greater than three Hz are substantially attenuated and isolated from the measurement apparatus **10.** Other realizations for the vibration isolator **36** are not excluded from this invention and should be obvious to those familiar with vibration isolator techniques.

[0034] Amplified electrical signals are provided to the acoustic projector **32** thru cables **38** that are interfaced to a power amplifier **40.** A test control and data processor **42** generates the electronic signals that are input to the power amplifier **40.**

[0035] In operation, acoustic signals are received on a plurality of calibrated reference standard hydrophones **44.** For the purposes of this invention, a calibrated reference hydrophone is simply a hydrophone that has been caibrated via some other means that is traceable to United States' standards through the National Institutes of Standards and Technology (NIST). Calibrated reference standard hydrophones are commercially available and known to those ordinarily skilled in the art.

[0036] A typical embodiment includes six to eight such hydrophones distributed over an inner surface of the measurement apparatus **10.** Electrical signals from the reference hydrophones **44** are transmitted over the cable **38** and received by the processor **42.** Electrical signals from the test article **100** are transmitted over a transmitting cable **46** and is received by the processor **42.** The measurement is performed from a floating test platform **200** that supports the equipment used to assemble and lower the measurement apparatus **10** into the water. The test platform **200** may include an enclosed laboratory space that houses the processor **42** and the power amplifier **40.** A common scenario employs a simple barge that is moored to the bottom or to the shore to maintain position and includes an enclosed laboratory space.

[0037] Acoustic data collected during the calibration measurement may be influenced by the presence of reflecting boundaries such as the platform **200,** water surface **300,** bottom **302** and any such objects as rocks **304** on or within the bottom.

[0038] **FIG. 2** illustrates a representative set of acoustic field components that are present when testing at frequencies that are less than that at which boundary reflections can be precluded by appropriate time gating of received signals. Essentially, this figure recognizes the existence of boundary reflections. The acoustic field radiated directly from the acoustic projector **32** prior to interaction with boundaries or other structures is generally representative of free field propoagation.

[0039] The prior art teaches various methods for the calibration of a hydrophone line array in an open body of water. These methods assume that this is the only acoustic field component present, or that all other field components combined, provide a neglible contribution to the acoustic field observed by the reference standard hydrophones and the line array. Other field componnents that are typically present at low frequency include surface reflection **400**, a contribution from a corner reflection **402** formed at the intersection of the floating test platform **200** with the water surface **300**, a bottom reflection **404** and reflections **406** from other objects on or embedded in the bottom **302**.

[0040] While information about the distribution and properties of these field components is frequently not adequate to develop an accurate, deterministic model of the acoustic environment; neglecting the field components can produce significant errors in the FFVS calculated for the hydrophone channels of the line array **100**. It is the intent of the invention to improve the precision and accuracy of the calibration result by accounting for the field components that are present, despite the absence of information needed to develop a deterministic physical model of the acoustic field.

[0041] The data channels of a hydrophone line array may number in the hundreds. The data required to compute the FFVS of these channels are collected simultaneously. The method begins with the generation of a signal with the properties of continuous broadband Gaussian noise. The signal is amplified and transmitted into the water by an acoustic projector such that the statistics of the acoustic field in the volume of water occupied by the measurement equipment are stationary.

[0042] Data provided by a plurality of calibrated reference standard hydrophones are processed using standard signal processing techniques to estimate the acoustic transfer functions between one of the reference standard hydrophones designated as the principle reference and all other reference standard hydrophones designated as auxiliary references. The acoustic transfer function H_{pn} between the principle reference p and the n^{th} auxiliary reference located at azimuth angle θ_n and vertical displacement z_n is given as the ratio of the cross spectrum P_{np} and the autospectrum P_{pp} of the principle reference as shown in Equation **(1)**.

$$H_{pn}(f,\theta_n,z_n) = \frac{P_{np}(f)}{P_{pp}(f)} \tag{1}$$

[0043] Frequency dependent, complex acosutic transfer functions computed using Equation **(1)** are then interpolated over the domain of azimuth θ and vertical displacement z that is occupied by the calibrated reference standard hydrophones on a frequency-by-frequency basis. The result is a purely empirical, frequency dependent model of acoustic wave field variations on the surface of the measurement apparatus **10**. By directly observing the acoustic transfer functions over the surface of the measurement apparatus **10**, the contributions from scattering and reflections are observed in addition to the direct path (or free field).

[0044] **FIG. 3** illustrates the magnitude of the complex acoustic transfer function over the cylindrical surface of the measurement apparatus **10** relative to the principle reference hydrophone located at an azimuth angle of zero degrees and a vertical displacement of zero meters. The radiating surface of the acoustic projector **32** is located on a longitudinal centerline **50** of the measurement apparatus **10** and at a vertical displacement of zero meters. The locations of eight reference standard hydrophones are illustrated with markers (e.g. Cross-hatched circles).

[0045] The figure shows that the acoustic field magnitude was not constant around the circumference of the measurement apparatus **10** as would be the case for propogation into free space without boundary reflections. On the contrary, azimuthal variations of more than two decibels were observed at a vertical displacement of one meter. **FIG. 4** shows that the corresponding variation in phase was more than fifteen degrees.

[0046] Calibration methods using a single reference standard hydrophone fixed to the surface of the measurement apparatus **10** will carry azimuthal variations in magnitude and phase directly into the calculation of FFVS as an error.

[0047] The complex, frequency dependent FFVS of the i^{th} sensor $M_i(f)$ in a hydrophone line array is given by Equation **(2)**:

$$M_i(f) = \frac{V_i(f)}{V_p(f)} \frac{M_p(f)}{H_{pi}(f, \theta_i, z_i)} \qquad \textbf{(2)}$$

[0048] where M_p and V_p are the FFVS and voltage observed on the principle reference standard hydrophone **44.** The voltage observed on the i^{th} hydrophone of the line array is V_i. The acoustic transfer function H_{pi} between the principle reference standard hydrophone **44** and the location of the i^{th} line array hydrophone is provided by the empirical model of the acoustic field variation on the surface of the measurement apparatus **10** as illustrated in **FIG. 3** and **FIG. 4.** All quantities in Equation **(1)** and **(2)** are complex valued. Equation **(2)** applies to the calculation of the FFVS for a single hydrophone in a towed line array.

[0049] Modification of Equation **(2)** is required when one or more data channels of the array are formed from a group of interconnected hydrophones that span a finite length as is done when spatial averaging is used as a noise reduction strategy. Equation **(3)** provides the FFVS when the i^{th} data channel is composed on an interconnected group of hydrophones that spans a length L along the longitudinal axis of the line array **100.** The value of the complex acoustic transfer function H_{pi} is replaced by the average value of the acoustic transfer function over the curve spanned by the hydrophone group.

[0050] The average value is represented by the line integral in the denominator of Equation **(3)** where the length of the hydrophone group is L and R is the radius of the cylindrical test fixture. The end points of the hydrophone group are located at azimuth angles θ_1 and θ_2. The vertical displacement of the group is assumed constant. The curve over which the integration is carried out is illustrated in **FIG. 3** and **FIG. 4** where the hydrophone group spans an arc length that is roughly half the circumference of the measurement apparatus **10**. Standard mathematic methods are used to estimate the value of the line integral and resultant average value for the acoustic transfer function on the curve spanned by a hydrophone group.

$$M_i(f) = \frac{V_i(f)}{V_p(f)} \frac{M_p(f)}{\frac{R}{L}\int_{\theta_1}^{\theta_2} H_{pi}(f,\theta,z)\, d\theta} \qquad \textbf{(3)}$$

[0051] where M_p and V_p are the FFVS and voltage observed on the principle reference standard hydrophone. The voltage observed on the i^{th} hydrophone group of the line array is V_i. The acoustic transfer function H_{pi} between the principle reference standard hydrophone and all points on the surface of the measurement apparatus **10** is integrated between the angular limits θ_1 and θ_2 spanned by the hydrophone group length of L. R is the radius of the measurement apparatus **10**. The vertical displacement z_i of the i^{th} hydrophone group is assumed constant and f is the frequency.

[0052] The method taught by this invention provides for in situ verification of the accuracy and precision achieved when calibrating an array. The verification is accomplished by treating one reference standard hydrophone as the test article **100** to be calibrated (used as a surrogate). Calculations described above are performed using the remaining reference standard hydrophones. The resulting FFVS is compared to the known FFVS for the reference standard hydrophone. This process is repeated for each of the reference standard hydrophones in a process commonly referred to as a round robin calibration.

[0053] Errors in the round robin calibrations of the reference standard hydrophones are then used to characterize the measurement uncertainty for the data channels of the test article **100** using standard statistical methods. **FIG. 5** illustrates the result of one round robin calibration with frequency compared to magnitude and **FIG. 6** illustrates the result of one round robin calibration with frequency compared to phase. As shown in the figures, errors in magnitude and phase of the FFVS are a fraction of one decibel over most of the frequency band. The limits over which an accurate calibration was achieved using this method are easily identifiable by the increase in the calibration uncertainty (e.g. error bars) at the minimum and maximum frequencies.

[0054] The present invention discloses a method to measure the complex sensitivity of data channels in a towed hydrophone line array. The major advantages are improved accuracy and precision at low frequency. Calibration methods described in the prior art presume free field acoustic propagation. The method of the invention observes and compensates for the actual acoustic field, including acoustic energy that is reflected from the surface, the floating test platform, the bottom and any other factors that would violate the acoustic free field assumption. In addition, the calibration method disclosed employs a vibration isolator in the lifting apparatus for the acoustic projector to isolate and attenuate vibrations that would otherwise contaminate the acoustic data collected with the test article and calibrated reference hydrophones.

[0055] It will be understood that many additional changes in the details, materials, steps and arrangement of parts, which have been herein described and illustrated in order to explain the nature of the invention, may be made by those skilled in the art within the principle and scope of the invention as expressed in the appended claims.

SYSTEM AND METHOD FOR THE CALIBRATION OF A HYDROPHONE LINE ARRAY

ABSTRACT OF THE DISCLSOURE

A method is disclosed for calibration of a towed line array. In a low frequency band, calibration is performed using an acoustic field observed by reference standard hydrophones. The observations form a model of a complex acoustic field throughout a space occupied by a measurement apparatus. The array sensitivities are computed by comparing output voltages of the array with the acoustic field estimated at the locations occupied by hydrophones of the array. Variations in the acoustic field that cannot be accounted for by free field propagation theory are included in the calculation of array channel sensitivities. The method extends the low frequency limit for the calibration to less than the minimum frequency at which free field propagation conditions can be approximated. Boundary reflections and spatial variations in the acoustic field are recognized. The spatial distribution of acoustic energy is used to provide low frequency calibration with improved precision.

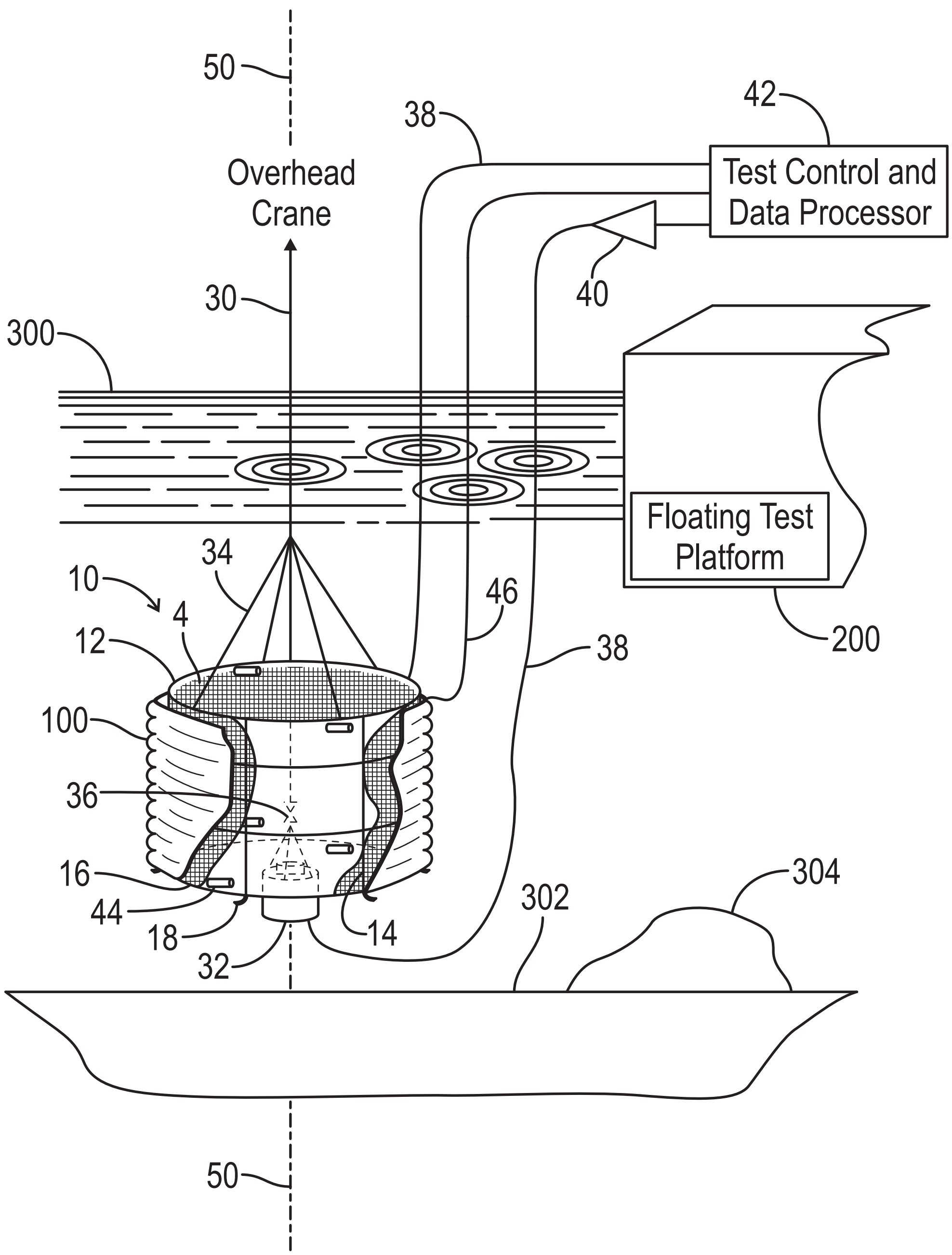
50
38
42
Overhead
Crane
Test Control and
Data Processor
30
40
300
Floating Test
Platform
34
10
4
46
12
200
38
100
36
16
44
18
14
302
304
32
50

FIG. 1

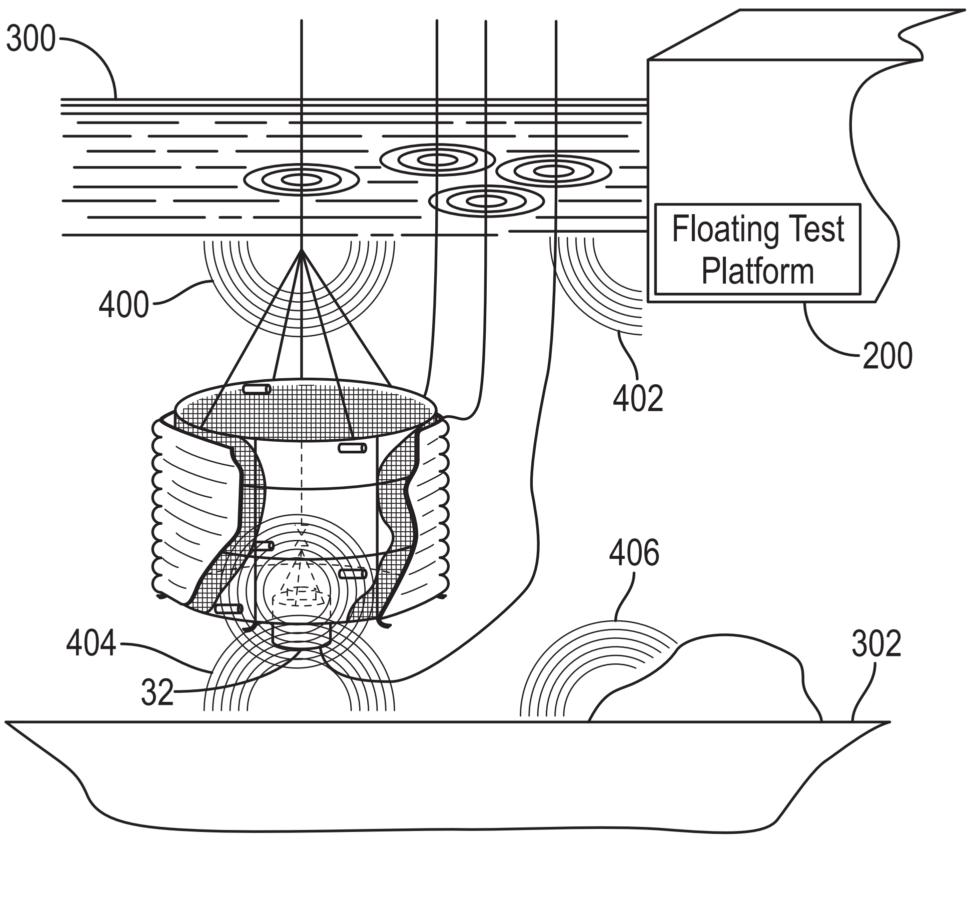

FIG. 2

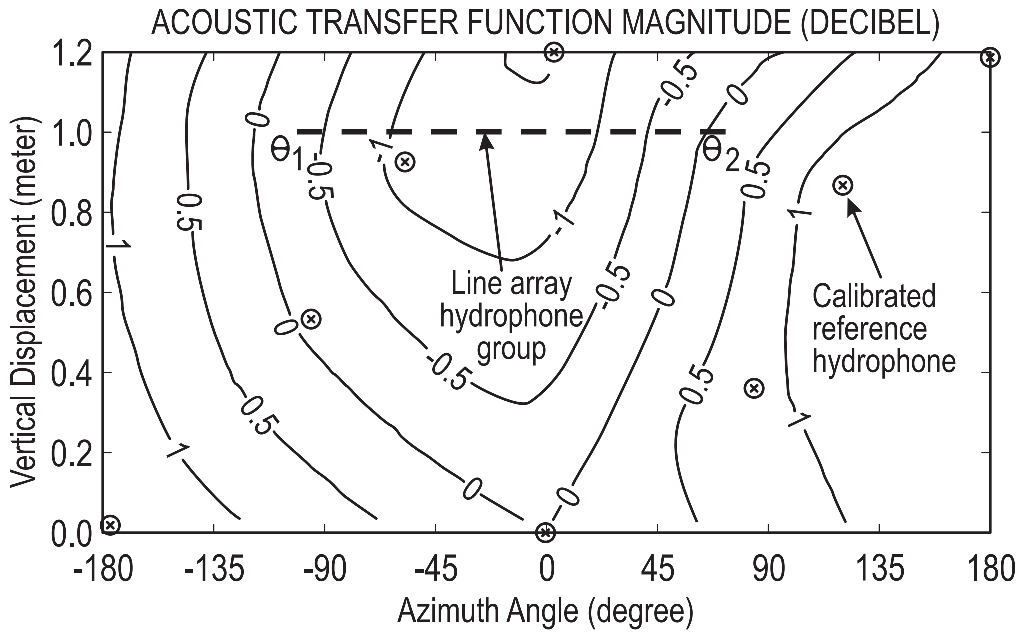
ACOUSTIC TRANSFER FUNCTION MAGNITUDE (DECIBEL)
Vertical Displacement (meter)
Azimuth Angle (degree)
Line array hydrophone group
Calibrated reference hydrophone
θ_1
θ_2
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-180
-135
-90
-45
0
45
90
135
180
1
0.5
0
-0.5
-1

FIG. 3

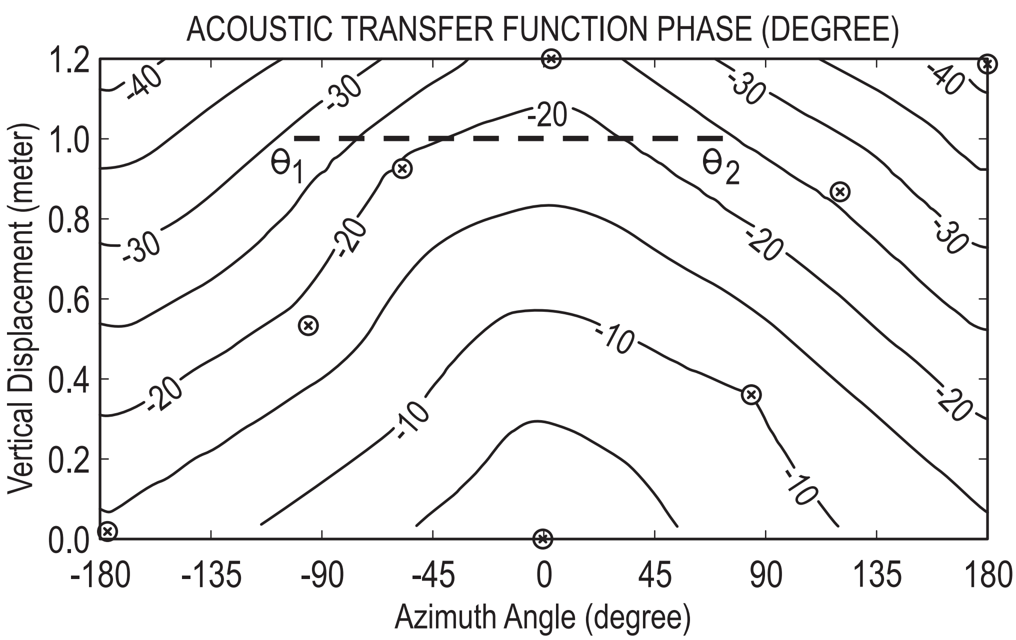
ACOUSTIC TRANSFER FUNCTION PHASE (DEGREE)
Vertical Displacement (meter)
Azimuth Angle (degree)
θ_1
θ_2
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-180
-135
-90
-45
0
45
90
135
180
-40
-30
-20
-10

FIG. 4

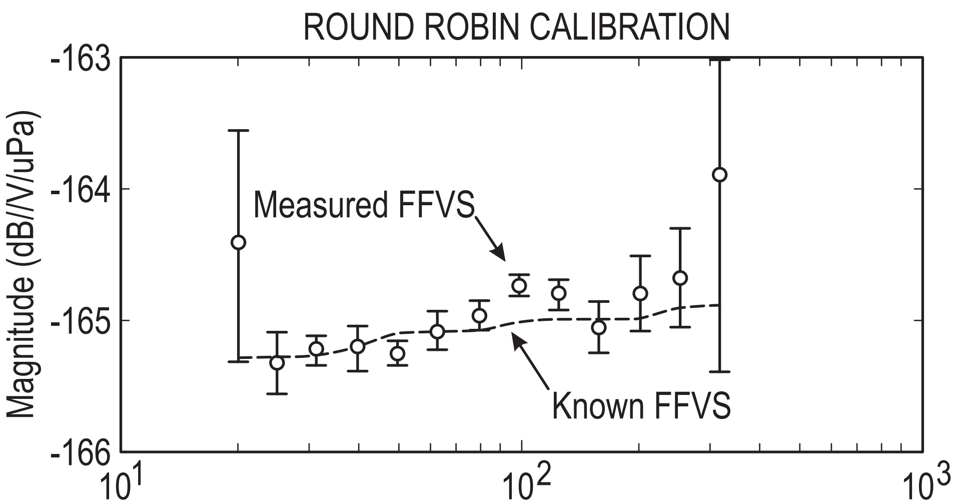
ROUND ROBIN CALIBRATION
-163
-164
-165
-166
Magnitude (dB//V/uPa)
Measured FFVS
Known FFVS
10^1
10^2
10^3

FIG. 5

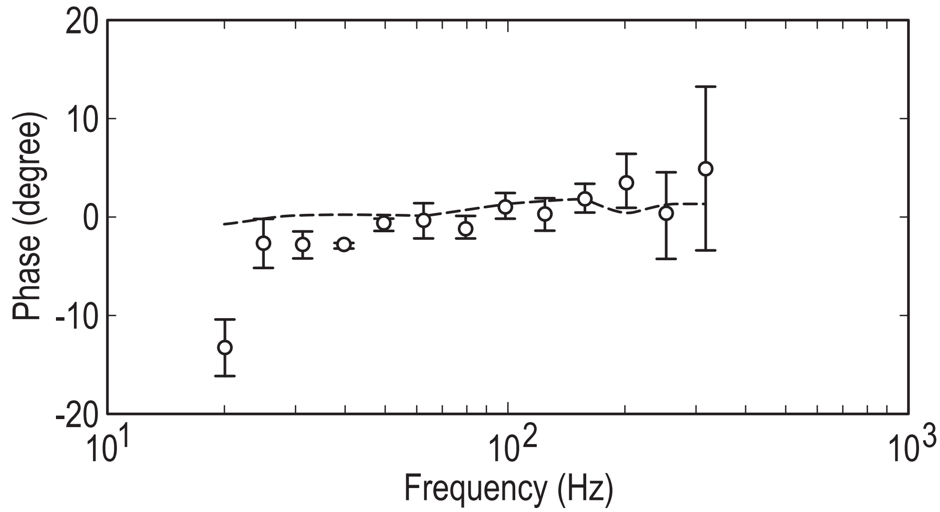
20
10
0
-10
-20
Phase (degree)
10^1
10^2
10^3
Frequency (Hz)

FIG. 6